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LIGHTWEIGHT SOLAR ARRAY BLANKET TOOLING, LASER WELDING, AND COVER PROCESS TECHNOLOGY

JPL CONTRACT NO. 956020

PAUL A. DILLARD

JANUARY 1983

FINAL REPORT

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-918.

LOCKHEED MISSILES & SPACE COMPANY, INC.
SPACE SYSTEMS DIVISION
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ABSTRACT

Lockheed Missiles & Space Company, Inc. (LMSC) has performed a two-phase technology investigation to demonstrate effective methods for integrating 50 micrometer thin solar cells into ultralightweight module designs.

During the first phase, innovative tooling was developed which will allow lightweight blankets to be fabricated in a manufacturing environment with acceptable yields. During the second phase, LMSC improved the tooling and confirmed the feasibility of laser processing of lightweight arrays. This report describes the development of the cell/interconnect registration tool (CIRT) and interconnect bonding by laser welding which occurred during the second phase.

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1.0 INTRODUCTION AND SUMMARY

Phase I of this effort, a technology investigation which determined the feasibility of manufacturing ultra lightweight, high performance solar arrays using 2 mil (50 μm) solar cells was reported in June 1982.[1] Early in this investigation LMSC determined the need for special tooling and handling methods that would cost effectively handle the 2 mil cell components during fabrication and test. A major achievement was the development of a module assembly concept which: (1) permits one-time handling of module components, and (2) is adaptable to many alternative interconnection processes. The resulting Cell Interconnect Registration Tool (CIRT) was used to manufacture a module coupon which, with 13% cells, would produce 345 watts per kilogram during phase I. Phase I accomplishments are summarized in Table 1. During phase II, the CIRT was further refined to make it adaptable to more cell sizes and configurations and module assembly processes. Phase II accomplishments are summarized in Table 2.

The critical elements of handling and cell welding demonstrated during this program show the need for additional cell and interconnect development. The back contact on the cell must provide IR "see through" for control of the welding process. The front contact should be located inboard from the cell edge to minimize cracking. For parallel gap welding the interconnect plating thickness must be precisely controlled to obtain consistent welds.

The solar array design concept developed during phase I used modules which were produced on the cell interconnect registration tool (CIRT) and subsequently integrated into panels as shown in Figure 1. This concept was retained during phase II, while refinining the CIRT design and evaluating laser welding.

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[1] LMSC D794970, Lightweight Solar Array Blanket Technology, JPL Contract No. 956020, dated June 1982

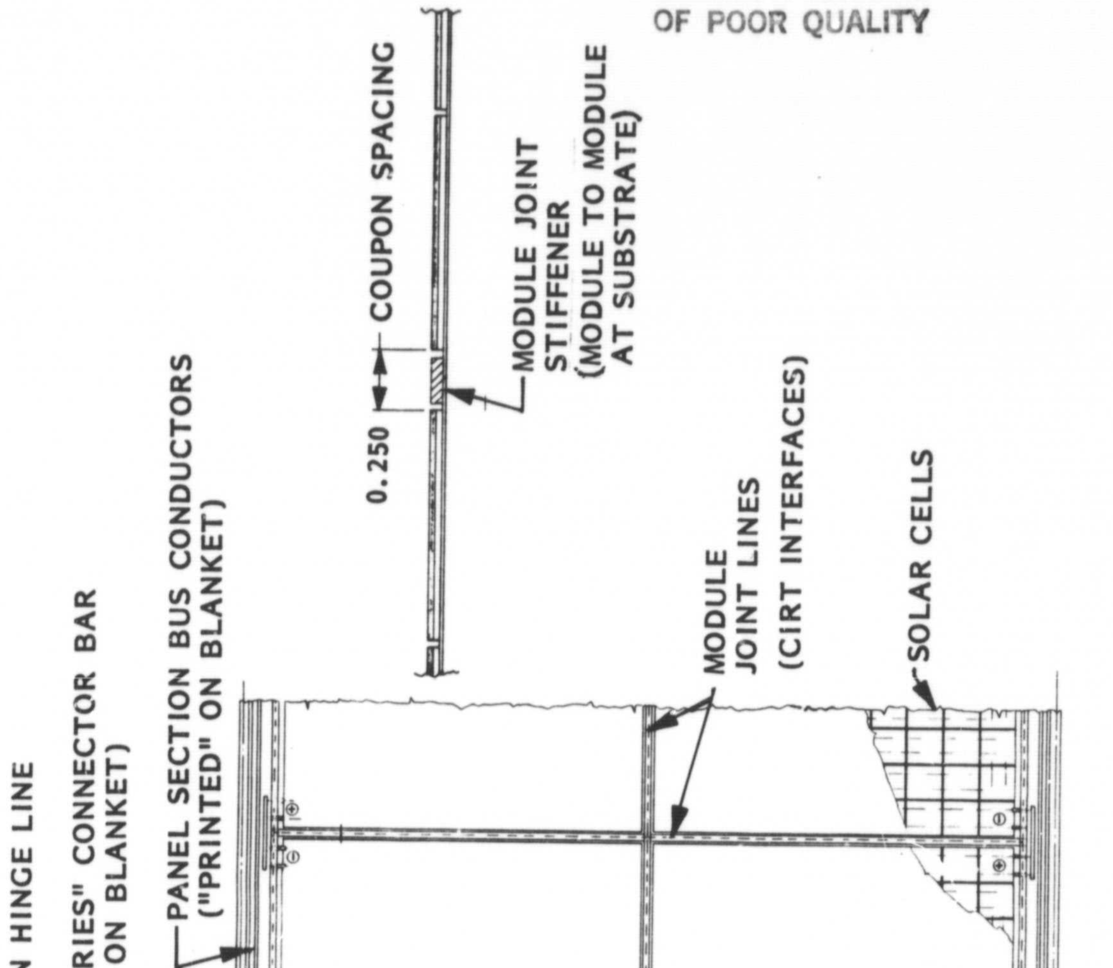


Figure 1 Ultralight Solar Panel Concept Showing Module Installation

TABLE 1

MAJOR ACCOMPLISHMENTS - PHASE I

- Designed and Demonstrated Cell Interconnect Registration Tool (CIRT)
- Defined Design and Production Method Which Minimizes Handling of Components During All Stages of Blanket Assembly
- Defined Technology Improvements Which Will Permit Fabrication of 600 W/kg Modules
- Investigated Feasibility of Laser Welding for Interconnecting 2 Mil Cells
- Produced 64 50-micron thick Cell Module Coupons On CIRT Demonstrating
  - P Welding with Weld Temperature Feedback Control
  - N Welding
  - Substrate Bonding
  - Vacuum Cover Bonding
- Produced 4 Cell Module Coupon on CIRT Demonstrating
  - Vacuum Cover Bonding of 2 Mil Superstrate Using 4 Mil 5.9 x 5.9 cm Wraparound Solar Cells

TABLE 2

THIN CELL BLANKET ACCOMPLISHMENTS - PHASE II (1982)

CIRT

Redesigned and Modified for:

- Coplanar Contact Cells
- Other Cell Sizes and Thicknesses
- Adhesive Control During Cover Bonding
- Superstrate Bonding
- Enlarged Access for P Contact Weld

Demonstrated by Preparing Work-In-Process Samples

LASER WELDING

Demonstrated Feasibility of Laser Welding of Solar Cells

COVER BONDING ON CIRT

Confirmed CIRT for Cover Bonding

Demonstrated Technique for Adhesive Control on CIRT

2.0 TECHNICAL APPROACH

2.1 CELL INTERCONNECT REGISTRATION TOOL (CIRT)

LMSC designed the Cell Interconnect Registration Tool (CIRT) to provide one-time handling of module components as they are installed. The components are not handled or moved until the module has been fully integrated into the array panel. All elements of assembly, processing, inspection, and testing are performed in the CIRT.

The Phase I Cell Interconnect Registration Tool (CIRT) was used successfully to produce an 8 cell x 8 cell coupon with frosted 2 mil covers and to install a 2 mil microsheet superstrate over four 5.9 cm x 5.9 cm cells in vacuum. During this phase the CIRT design development included:

- Improving access to components for welding
- Adding and/or defining provisions for adhesive control and cleaning
- Improving provisions for cell/interconnect support, particularly under parallel gap weld forces

This effort resulted in the following changes, some of which are also shown in Figures 2 and 3.

- Improved Access to Back of Cells
    - Larger windows
- Temperature Sensing/Control for N and P Welds
    - Aligned windows for:
        1. P welds for all known cell sizes, thicknesses
        2. N welds for rearranged contacts (moved inboard) on conventional cells and for most N contact configurations on wraparound cells

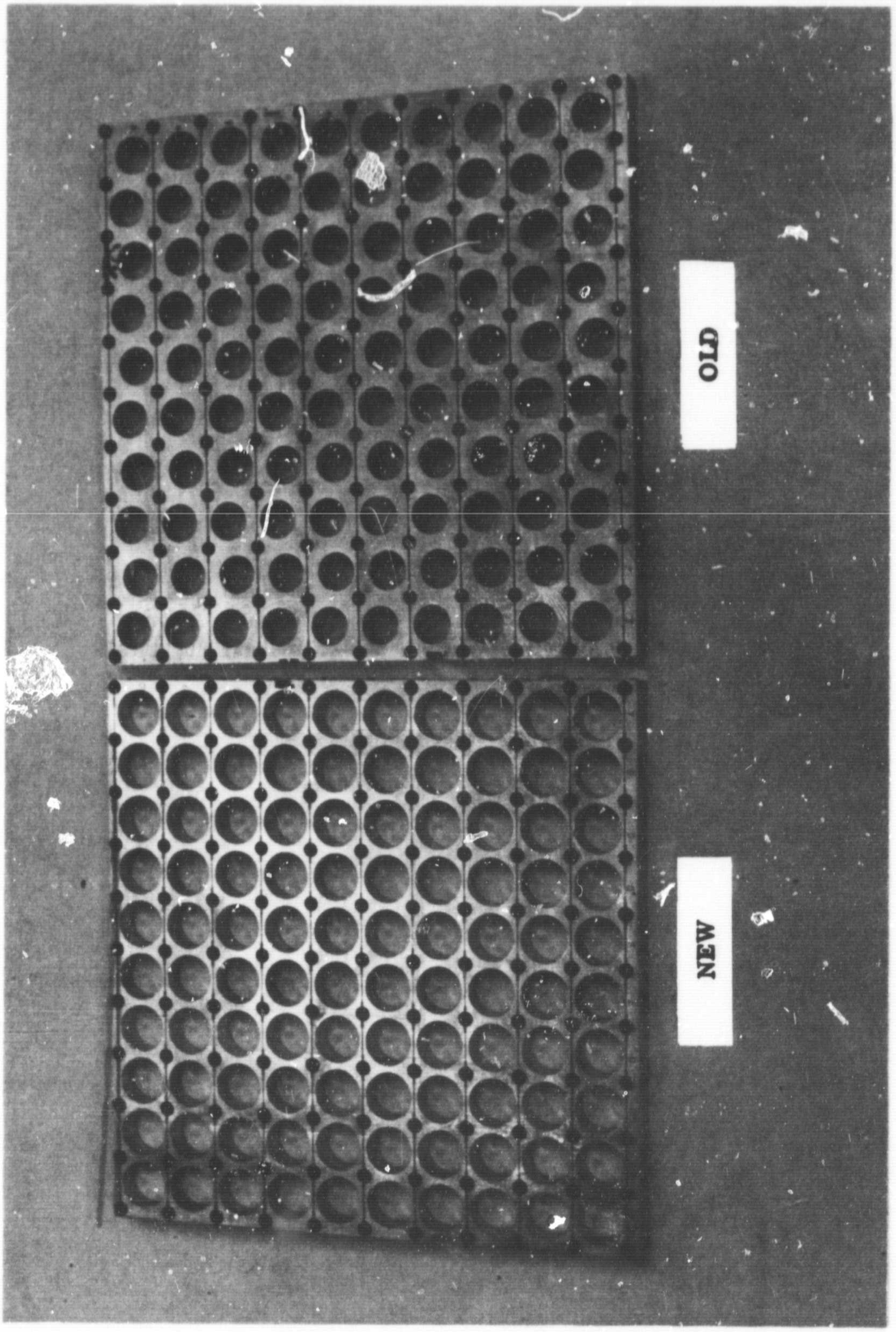


Figure 2 Old and New CIRT

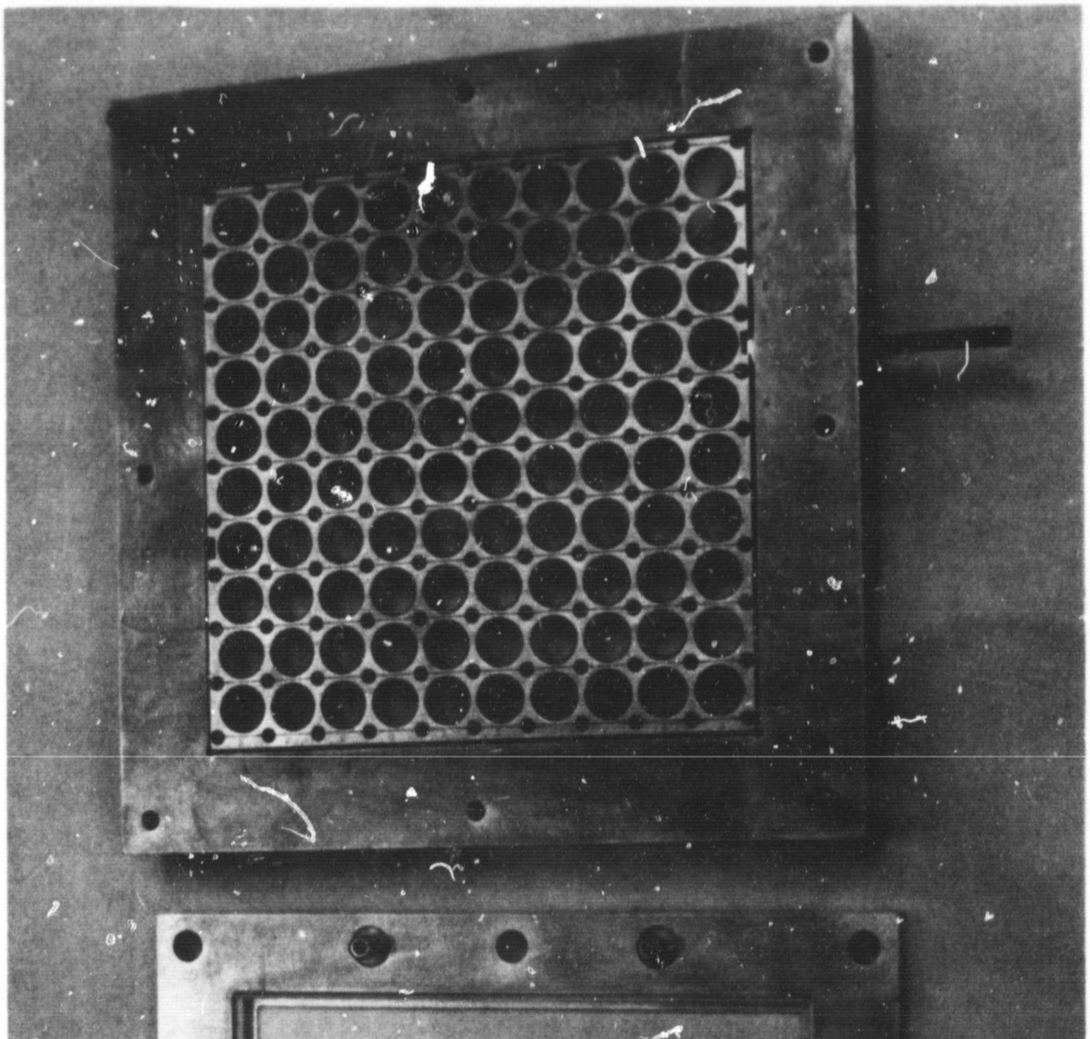


Figure 3 New CIRT with Modified Vacuum Chamber

- Provisions for Adhesive Control and Cleaning
  - 1. Replaced bonded foam springs with stainless springs with snap rings for cleaning
    2. Defined method for absorbing excess adhesive which minimizes total contamination
- Improved Cell Support
  - Larger windows with larger bond area reduce the chance of flexure during weld

The modified CIRT was used successfully during the cover bonding tests as discussed in Section 2.3 of this report.

2.2 LASER WELD EVALUATION

Laser welding of the interconnect to thin cells offers a number of advantages over conventional techniques. Precise control of energy input, pulse duration and area of impingement is readily achieved, and the process does not impose large external stresses on the cells. It only requires that the interconnect be held in intimate contact with the cell surface during the welding cycle. The beam energy is applied to a small spot on one side of the tab, heating it sufficiently so that the heat can penetrate by conduction through the tab to cause the mating surfaces to form a suitable bond.

Laser welding of interconnects to conventional solar cells has been successfully demonstrated at LMSC, and experimental work using CO_2 and Nd-YAG lasers has shown that joints of adequate pull strength can be made to thin cells. Although further work is needed to determine the effect of various laser weld parameters on joint strength and cell performance for both P-side and N-side welds on thin cells, the results of this effort show promise in the following areas:

- Alternate laser systems
- Coupling of the laser beam energy into the workpiece
- Enhancing bonding at the interface while minimizing heat input
- Several different tooling methods have been demonstrated

This task examined and confirmed the suitability of using laser technology for welding of thin cell modules on the CIRT.

The results of this effort are:

- Confirmation of the feasibility of laser welding interconnects to thin cells
- Definition of some effects of laser weld parameters on joint strength and cell performance
- Recommended equipment for array production with CIRT

This effort included the following interconnect materials:

- 1 mil molybdenum with Ag on both sides
- 1 mil molybdenum with Ag on one side
- 1 ounce copper
- 1.5 mil aluminum

2.2.1 Equipment

Raytheon Model SS-501B-7 Pulsed YAG Laser

The majority of the welding in this study was done with the Raytheon Model SS-501B-7 Precision Laser Welder/Driller shown in Figure 4. This unit incorporates a high-power high pulse-rate Nd:YAG laser of advanced design which permits convenient, independent adjustment of the basic variables which are important for precision laser welding and drilling (average power, peak power, pulse length, pulse rate, pulse energy and power density). Table 3 lists the specifications of this unit. Major components of the laser system are the laser head, power supply, pulse forming network, optical system, water cooling system, and control panel.

TABLE 3

SPECIFICATIONS OF RAYTHEON MODEL SS-501B-7 LASER

Wavelength	1.06 microns
Rated Average Power	400 Watts
Rated Maximum Pulse Energy	50 Joules
Pulse Rate (continuously variable)	1 to 200 pulses/second
Pulse Length (variable)	0.25 to 7.2 msec
Focused Beam Spot Diameter (continuously variable)	.005 to .075 inches*

*Smaller spot sizes down to approximately .001 inches may be obtained by using cavity apertures

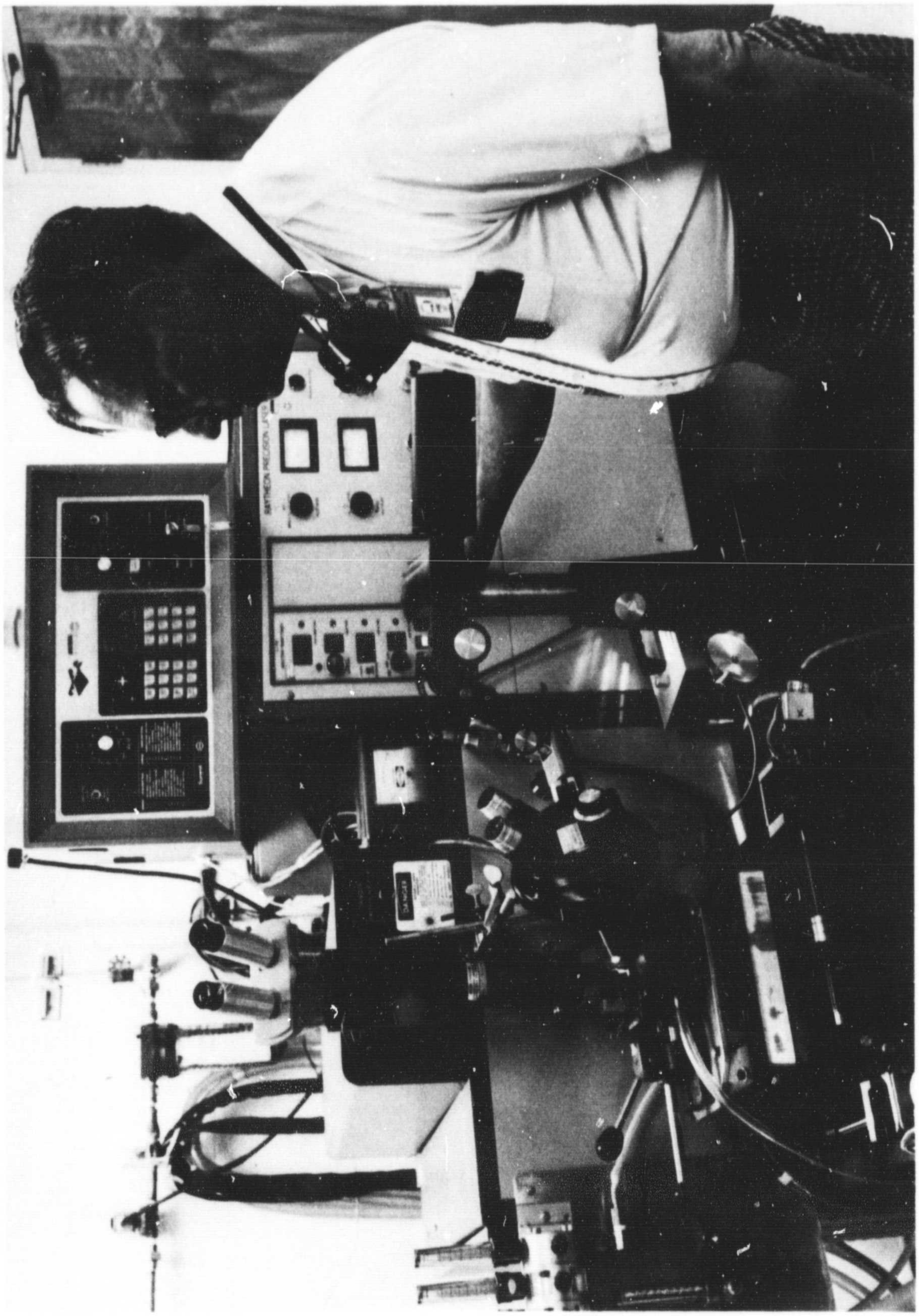


Figure 4 Laser Weld Station

The laser head incorporates a single, large Nd:YAG crystal and two large linear krypton flashlamps in a single, high efficiency, dual elliptical cavity. The lamps and laser rod are water cooled and provision is made for quick replacement of lamps without disturbing the optical alignment. Other components of the laser head include front and rear mirrors, gimbal mounted with precision micrometer adjustment for alignment, and provision for placing an aperture in the beam path to control mode.

The power supply consists of a voltage regulated DC power supply, a capacitor bank, an adjustable, multi-loop, L-C pulse forming network, and various control switches and relays. The pulse forming network provides for a wide selection of pulse lengths and also permits control of the pulse shape from a short, high peak power, half sine wave pulse used for drilling, to larger square wave pulse shapes used for welding.

The optical system, a schematic diagram of which is shown in Figure 5, is bolted to the laser head to form an integrated laser-optical system for controlling the laser beam and focusing it on the workpiece. Components of the optical system include a high-speed beam control shutter (1) which deflects the beam into a water-cooled beam absorber (2) or onto the workpiece as required, a beam expander (3) which expands the beam issuing from the Nd:YAG rod, a dichroic mirror (4) which deflects the expanded beam vertically downward where it passes through the focusing lens (5) before impinging on the work. A protective gas nozzle (6) is provided to protect the focusing lens against spatter and vapor deposits. A binocular microscope (7) with an alignment cross hair is provided for positioning the focused beam on the workpiece. Viewing is coaxial with the laser beam. A blade-type safety shutter (8) automatically prevents viewing through the microscope during laser operation, and a high attenuation filter (9) is permanently placed in the microscope viewing path as a second protection against possible 1.06 micron laser radiation. A silicon photodiode, continuous reading, average power monitor (10, measures the leakage radiation transmitted through the rear laser mirror and is calibrated to display average output laser beam power on a meter. A pulse monitor function is also available for observing the laser pulse shape with an oscilloscope.

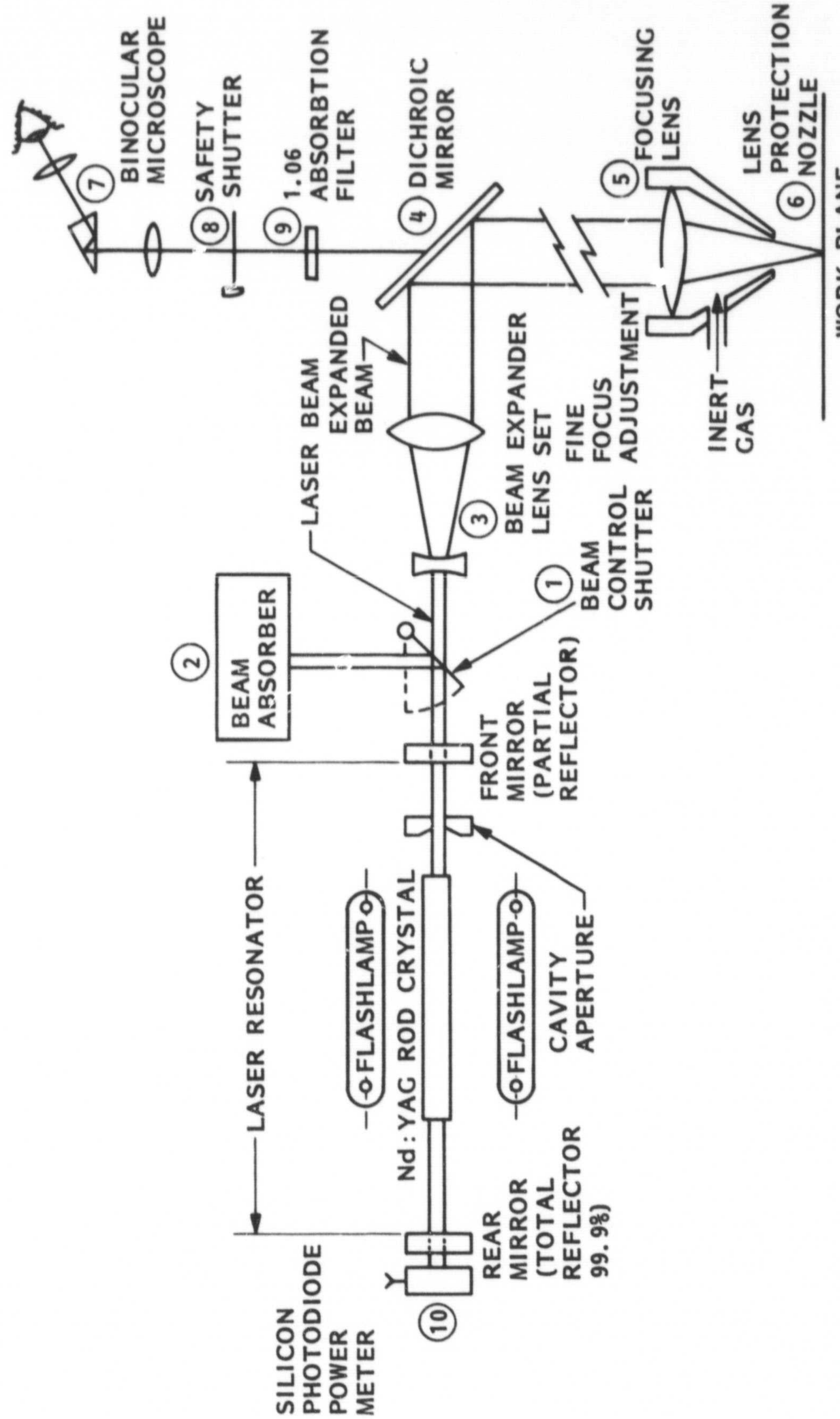


Figure 5 Optical System Schematic Diagram

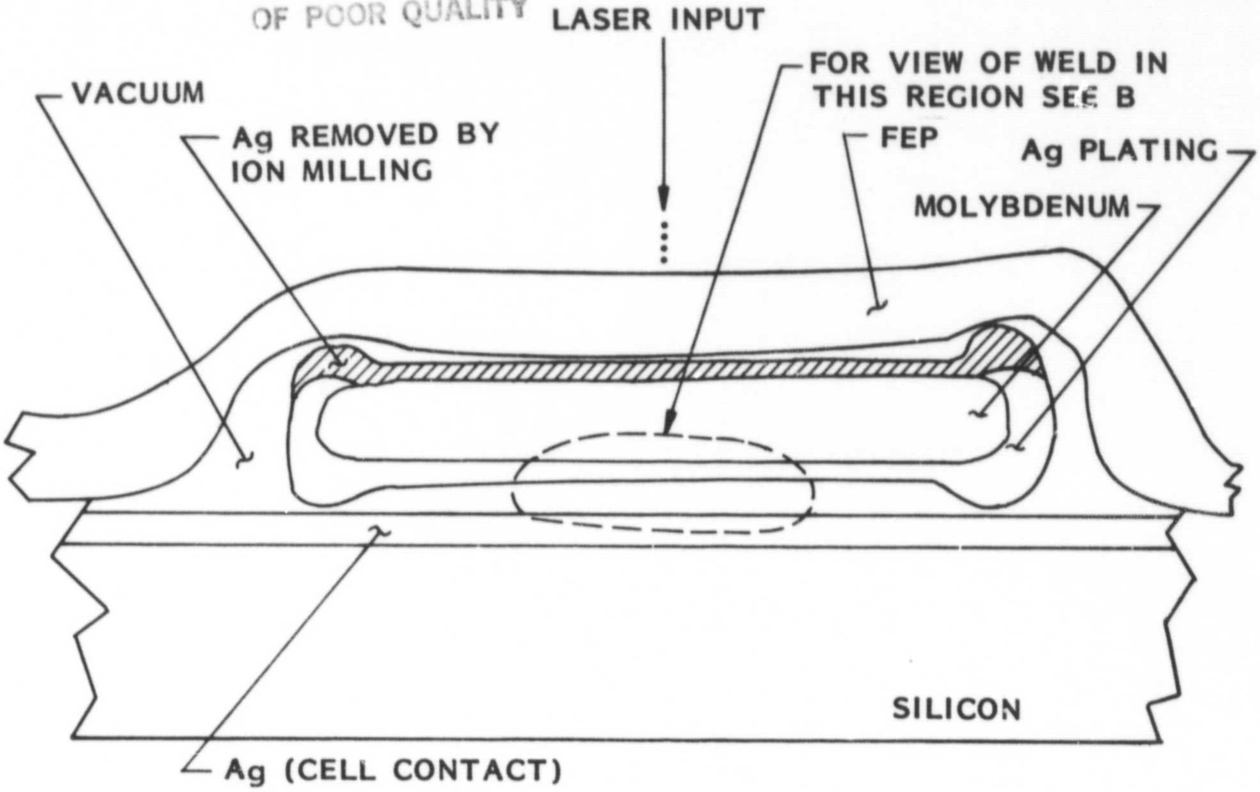
The water cooling system provides a closed-loop flow of deionized, temperature-regulated water to cool the laser flashlamps, cavity and beam absorber. The control panel incorporates a standby on-switch, high voltage on and off switches, a PEN adjust knob to set the laser pulse peak power, and PFN Voltmeter, a lamp power meter which indicates the power input to the laser flashlamps, and a series of pulse controls to select either single or repetitive pulses and to set the pulse rate. A pulser switch is used to initiate pulsing.

The control panel also includes a plug-in beam shutter control, which can be set for manual or automatic operation. Timing sequences available in automatic operation include pre-weld delay time, weld time, ramp time (in which the laser energy is reduced or "tapered off" at a slope set by a slope adjust potentiometer) and post ramp time during which the laser fires at the minimum energy level selected.

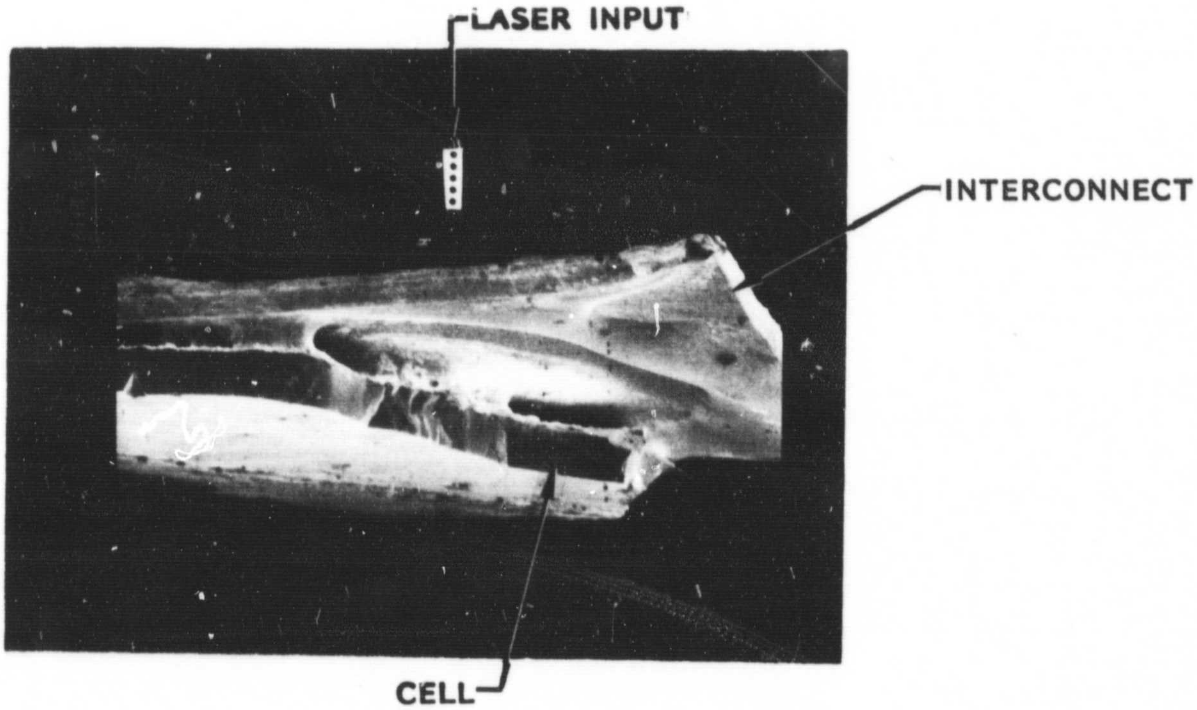
2.2.2 Component Fixturing During Laser Welding

Prior laser welding experiments led to speculation that oxidation occurs and inhibits welds which are performed in air. This suspicion and the fact that the CIRT was not available led us to devise the vacuum hold down scheme shown in Figure 6. After the cell and interconnect are aligned they are covered with a thin film of FEP Teflon and evacuated. The film admits the laser energy while the vacuum inhibits oxide formation. Some boiloff occurred during welding as evidenced by black material which recondensed on the FEP after the weld. This film-vacuum hold down method could be adapted for use on the CIRT, offering another level of flexibility.

Plated interconnects exhibit silver build-up on the edges of the interconnect which prevents uniform contact of the joining surfaces (see Figure 6 (a) and (b)). Correcting the problem would require development of controls in the plating operation. An alternative design would punch the interconnect pattern from a sheet of silver-clad or plated molybdenum.



a. Early Laser Weld Configuration



b. View of Laser P Weld (100X)

Figure 6 Laser Weld Fixturing and Resulting Weld

Another approach would be to coin or emboss a small projection in the center of the interconnect to ensure intimate contact at the joint. Some samples were prepared in this manner using a Rockwell Superficial Hardness Tester and a 1/16 inch diameter ball indenter to produce a 1-mil high, 25-mil diameter spherical projection in the center of the interconnect tab. Several satisfactory welds were then made to 2-mil solar cells using the Teflon film and vacuum for holding the parts (see Figure 7). Shortage of time prevented further evaluation.

2.2.3 Spatial Uniformity of the Laser Beam

High-power lasers exhibit extremely non-uniform intensity distributions within the beam, producing "hot spots" within the laser spot on the surface of the workpiece. To reduce this non-uniformity it is common practice to introduce apertures within the cavity which limit the number of modes in operation but at a considerable loss in output power. For most laser applications this Gaussian distribution is ideal, but for welding of solar cell interconnects a uniform energy distribution is required. Early tests on aluminum and copper exhibited this problem. Subsequent tests used molybdenum which is more tolerant.

The laser beam uniformity of each of the lasers is characterized by expanding the beam and recording the pattern in burn marks on each of the coated interconnect materials to determine the uniformity of surface melting. Subsequently confirmed by electron beam tests, the patterns show a dewetting of plating and punch through of solid material. These show that improved beam uniformity is needed. A new type of beam homogenizer with very high beam energy throughout shows promise for implementation in the laser system for use with the CIRT.

2.2.4 Coupling the Laser Beam Energy Into the Material

Most metals reflect a major proportion of the incident laser light. This reflectance generally increases with wavelength giving an advantage of Nd:YAG lasers at 1.06 microns over CO_2 lasers at 10.6 microns. When a low power laser beam impinges on a polished metal surface, there is no melting because the light is largely reflected. As power is increased, however, there is a sudden increase in absorption resulting in surface melting and/or vaporization. With thin metal

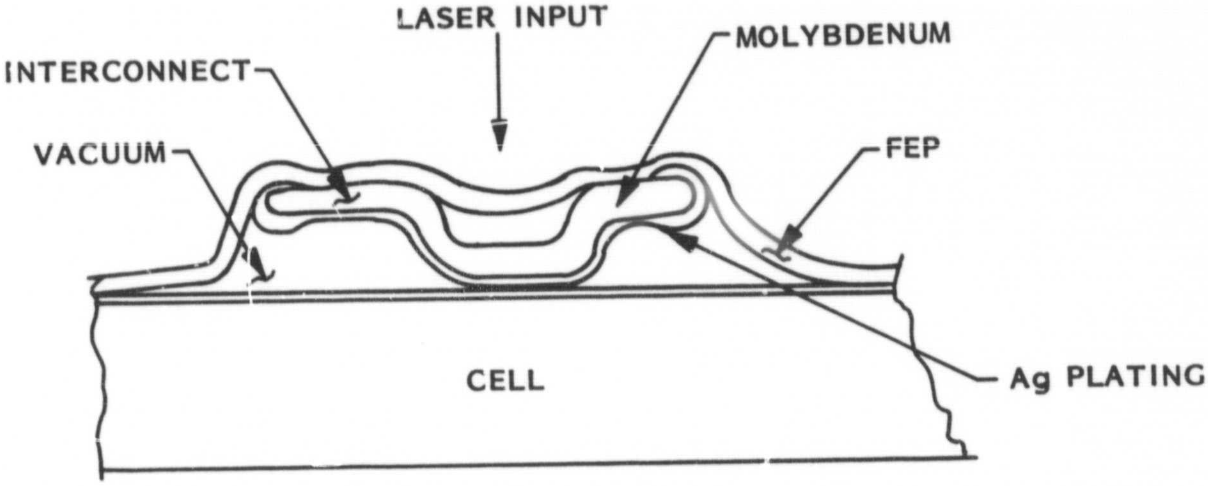


Figure 7 Improved Laser Weld Configuration with Embossed Projection on Interconnect

interconnects, the beam intensity necessary to overcome surface reflectivity can result in a catastrophic vaporization of the interconnect tab and penetration of the laser beam completely through the underlying silicon substrate.

An effective way of avoiding this problem is to change the incident surface of the tab so that it is a better absorber, thereby greatly reducing the required beam power. For example, by oxidizing a polished copper surface to provide a thin (~1 micron) CuO/Cu_2O film the reflectance can be reduced from approximately 95% to about 20%. Similar treatments can be applied to silver or aluminum surfaces. With judicious selection of a surface treatment, it should be possible to significantly reduce the power required for a laser weld, thereby minimizing possible substrate damage.

From a review of literature on absorbing selective coatings for the interconnect materials that were studied, promising treatments were selected for evaluation (see Table 4). Samples were prepared and evaluated for appearance and uniformity of the coating as well as stability. For the silver-plated molybdenum interconnects, both the polysulfide and the ion-beam texturing treatments were selected for further evaluation with laser beam, and for copper interconnects, both polysulfide treatment and the proprietary Ebanol-C treatment were selected. For the aluminum interconnects, only the black anodize treatment was evaluated.

Samples prepared by the above techniques were evaluated using a single pulse from the Nd:YAG laser focussed to a spot approximately 1 mm in diameter on the treated surface. The energy required to initiate melting of the metal underlying the absorptive coating was used as a means of rating the treatments. In the case of the silver-plated molybdenum foil, melting of the silver on the untreated side was the criterion and melting of the molybdenum was avoided.

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TABLE 4

SURFACE TREATMENTS TO ENHANCE COUPLING

INTERCONNECT MATERIAL	TREATMENT	REMARKS
1-mil Molybdenum (silver plated both sides)	Polysulfide	Dark gray appearance, excellent absorption.
	Ion Beam Texturing	Ion beam removes silver and textures molybdenum surface to a "matte" finish with good absorption.
1 ounce Copper Foil	Vapor Hone (abrasive finish)	Gives a "matte" finish as treated but tends to stain after several days.
	Black Nickel Oxide	Uneven gray coating. Tends to stain.
	Polysulfide	Dark gray appearance, good absorption.
	Black Copper Oxide (EBANOL-C)	Dark gray appearance, most uniform "blackening" of the copper treatments. Good absorption.
1.5 mil Aluminum	Black Anodize	Very uniform blackening with excellent absorption.

In welding of interconnects, it is essential that the depth of penetration of the heat be closely controlled to avoid damage to the underlying solar cell. The depth of penetration of heat in a time (t) is given approximately by the equation:

$$Z = (4kt)^{1/2}$$

Z = depth of penetration
k = thermal diffusivity

For an interconnect of a given material and thickness this can be restated as a thermal time constant which represents the pulse duration required for the heat to completely penetrate the interconnect. Thermal time constants for various thicknesses of several materials of interest are given in Table 5. From this table one can see that the time necessary for the heat of the incident laser beam to penetrate through the interconnects of interest is of the order of microseconds and therefore very short pulse lengths should be desirable. One difficulty, however, arises from the fact that short pulse lengths of the order of microseconds tend to raise the material in the incident spot to its vaporization point and are in fact used for laser drilling. Longer pulse lengths, of the order of milliseconds, are used for welding where vaporization is to be avoided. For the initial evaluation of the various coupling treatments a pulse length of 1.3 milliseconds was selected, and single pulses at energy levels from 0.1 to 10 Joules were used giving a range of power density from about 10^4 to 10^6 watts/cm^2. All the interconnect materials in the untreated condition withstood in excess of 10 Joules without any visible effect. After treatment, however, melting of the underlying surface was observed with as low as 0.1 Joules. In the case of the black anodized aluminum, however, vaporization followed closely upon melting and it was not possible to just melt without producing a hole.

Figure 8 shows the effect of the laser energy level of a 1.3 m/sec pulse on penetration of the polysulfide treated silver-coated molybdenum. Below 1.0 J melting of the silver on the underside was achieved without melting of the molybdenum; above 2.0 J the molybdenum melted in the center and because of its high surface tension, a hole resulted. One unforeseen outcome of the screening tests with the silver-plated molybdenum interconnect material was the observation that the silver on both sides of the interconnect tended to "dewet"

TABLE 5

THERMAL TIME CONSTANTS OF SELECTED METALS

Thermal Time Constant (t) = Pulse duration to penetrate material of thickness (x) and thermal diffusivity (k)

$$t = \frac{x^2}{4k} = \frac{\text{sheet thickness}^2}{4\ (\text{thermal diffusivity})}$$

METAL	THERMAL DIFFUSIVITY IN^2/SEC	SHEET THICKNESS (in) .0001	.001	.002	.005
Silver	0.265	9.4 n sec.	0.94 u sec.	3.8 u sec.	23 u sec.
Copper	0.177	14 n sec.	1.41 u sec.	5.6 u sec.	35 u sec.
Aluminum	0.141	19 n sec.	1.90 u sec.	7.5 u sec.	47 u sec.
Molybdenum	0.079	29 n sec.	2.9 u sec.	1.2 u sec.	72 u sec.
Nickel	0.037	104 n sec.	10.4 u sec.	42 u sec.	260 u sec.
Stainless Steel	0.0064	416 n sec.	41.6 u sec.	156 u sec.	977 u sec.
Silicon	0.082	30 n sec.	3.0 u sec.	12 u sec.	76 u sec.

n = nano (10^{-9})

u = micro (10^{-6})

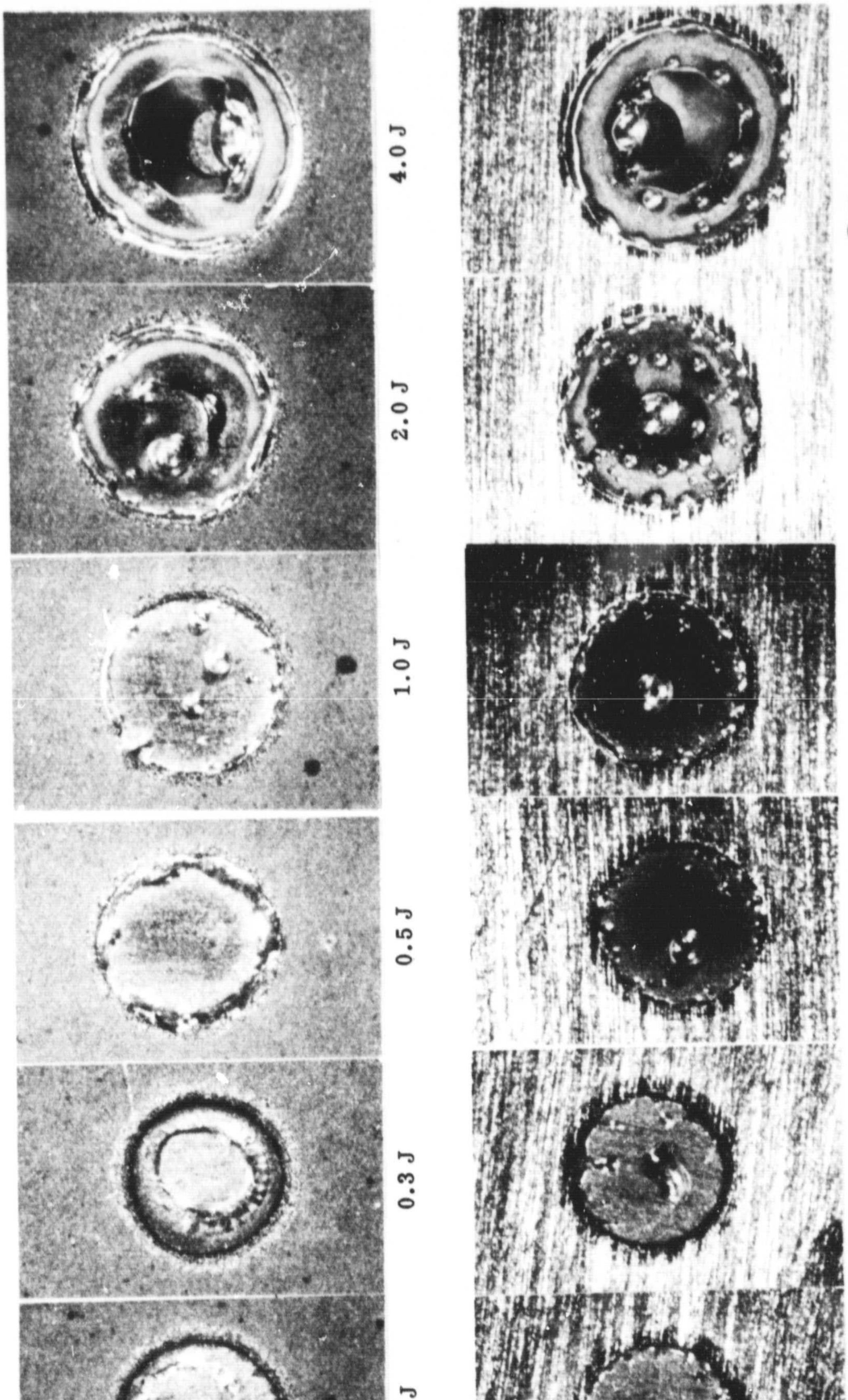

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Figure 8 Effect of Laser Energy Level on Penetration
1-Mil Molybdenum-Silver Coated (Polysulfide Treated on Top Side)
1.3 m sec Pulse Length

in the area heated by the laser beam. The hypothesis that the dewetting was caused by oxidation in air was disproved when similar results were obtained using an electron beam. The effect of lower energy level on penetration of 2-mil Ebanol treated copper is shown in Figure 9. Penetration was achieved at 0.2 J producing a small molten bump on the underside in the center of the spot. A larger area was produced at 0.5 J, whereas at 1.0 J a hole through the interconnect resulted.

It was then decided to increase the pulse length to 7.2 milliseconds to decrease the power density and hopefully decrease the tendency for dewetting and "holing-thru." Figure 10 shows a series of spots made on polysulfide treated silver-coated molybdenum using a 7.2 m-sec pulse. At the higher energy levels there was a tendency for "dewetting" on both the top and bottom similar to the previous series with the 1.3 m-sec pulse length, but below 0.5 J "dewetting" did not occur. Similar results were obtained with the ion-milled molybdenum as shown in Figure 11, except that the threshold level was at 1.5 J. It would appear that the ion-milled molybdenum surface is not as efficient a coupling agent as the polysulfide treated silver; however, it has other advantages in eliminating any molten or vaporized metal or fumes in the area of impingement and thus was selected for use in the subsequent studies.

2.2.5 Laser Weld Tests

Several experiments were designed to establish thresholds for cell damage and contact melting and to determine the range of energy input in which laser welds can be made with minimal influence on cell output. Several experiments were run with different locations of components and areas of laser beam impingement. Cells from three different vendors were to be evaluated including two types of cells from one vendor. Three methods of evaluation were used, namely, electrical test, visual examination, and pull testing.

Using weld parameters established in the previous section, two sets of experiments were completed on the Spectrolab cells. Pull strength data for the Spectrolab laser welded samples is shown in Table 6.

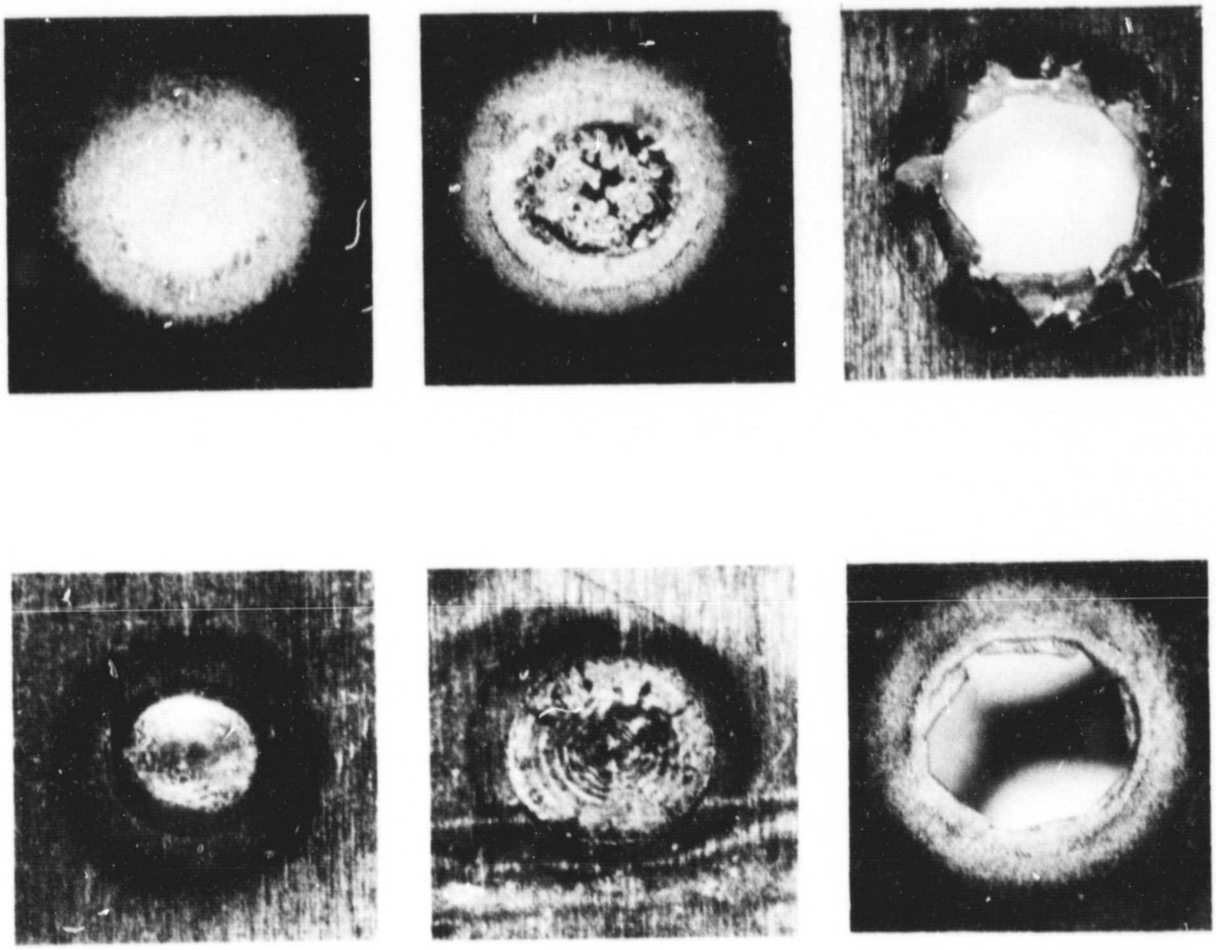
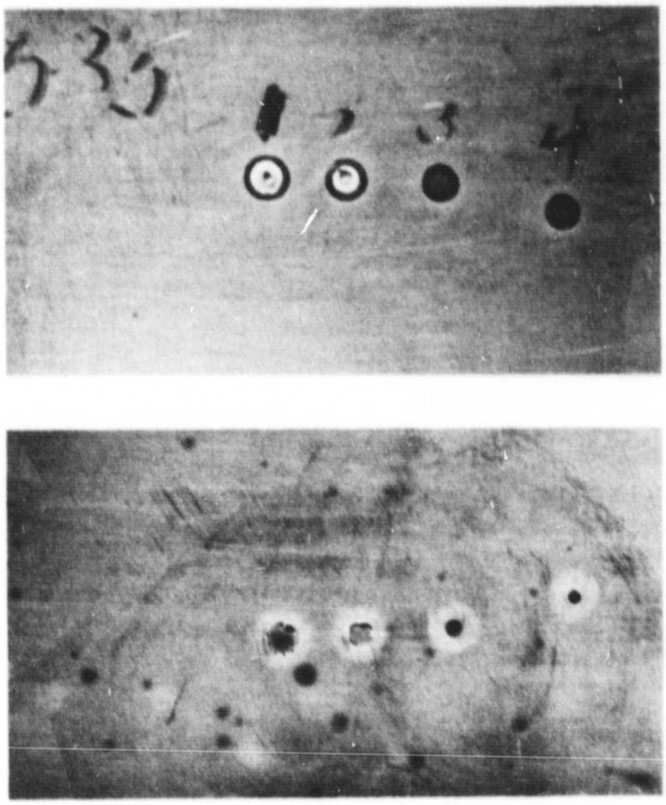


Figure 9 Effects of Laser Energy Level on Penetration
2-Mil Ebanol Treated Copper



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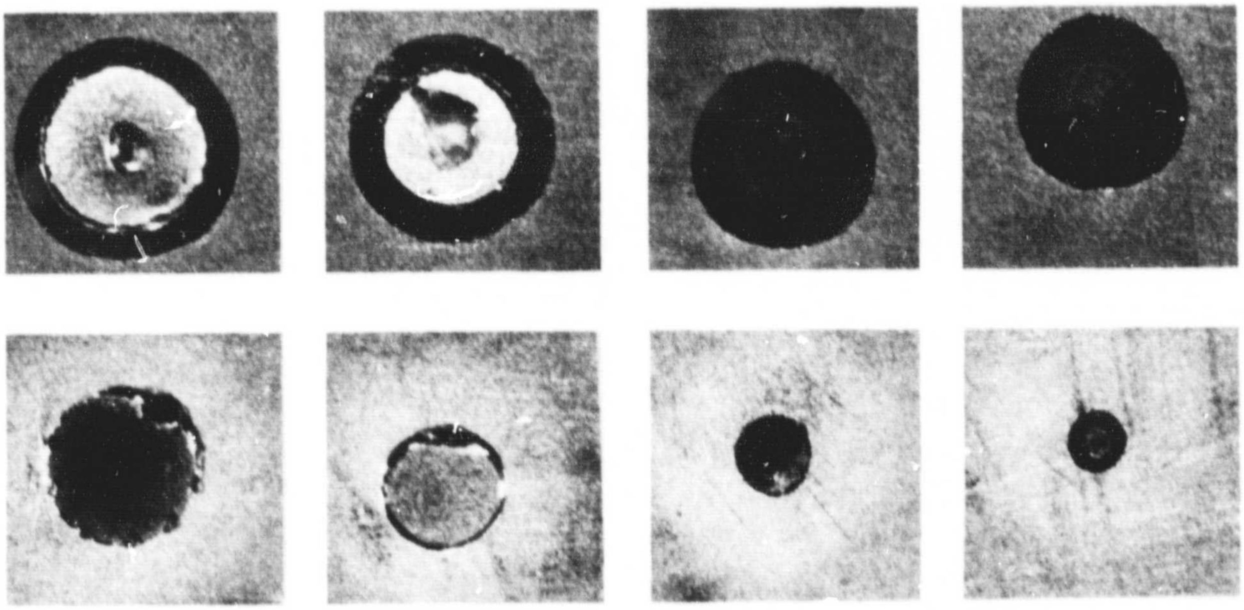


TOP

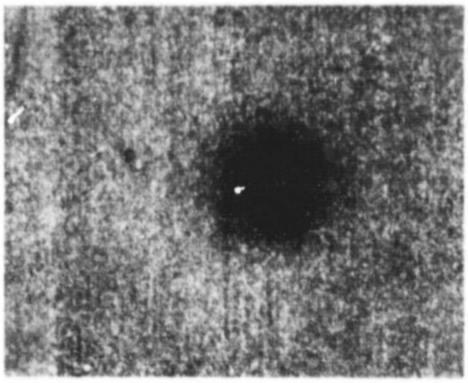
BOTTOM

25 X

1.0 J	0.75 J	0.5 J	0.4 J
.032 in. Dia.	.024 in. Dia.	.016 in. Dia.	.012 in. Dia.

Figure 10 Effect of Laser Energy Level
1-Mil Ag Coated Mo (Polysulfide Treated on Top Side)
7.2 m sec Pulse Length

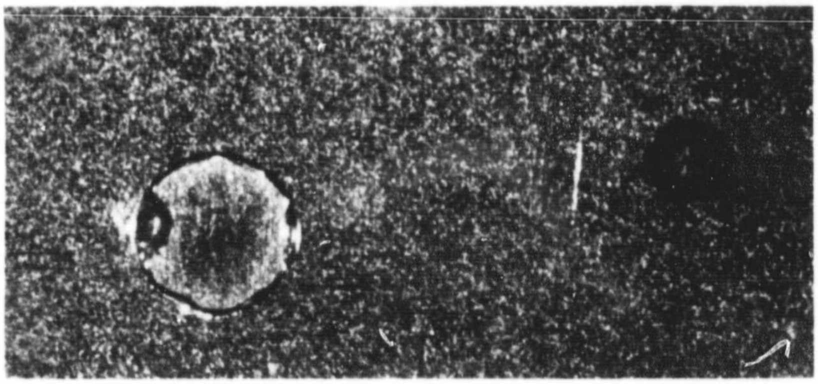
TOP



(SPOT NOT VISIBLE)

25 X

BOTTOM



2.0 J
0.038 in. Dia.

1.5 J
0.016 in. Dia.

25 X

Figure 11 Effect of Laser Energy Level
1-Mil Ag Coated Mo (Ion Milled on Top Side)
7.2 m sec Pulse Length
1-Mil Teflon "Hold-Down"

TABLE 6

PULL STRENGTH DATA FOR LASER WELDED SAMPLES

2-MIL SPECTROLAB CELL - 45° PULL TEST

SERIES A (INTERCONNECT WELDED TO P-CONTACT)

WELD NUMBER	ENERGY LEVEL (J)	PULL STRENGTH gm**	FAILURE MODE
545-6	1.5	80	Metallization Failure
545-7	1.8	140	Divot Failure
545-8	2.0	120	Divot Failure
545-10	2.25	140	Divot Failure
545-11	2.5	140	Divot Failure

SERIES B (INTERCONNECT WELDED TO N-CONTACT)*

WELD NUMBER	ENERGY LEVEL (J)	PULL STRENGTH gm	FAILURE MODE
548-4	0.3	65	Metallization Failure
548-2	0.5	95	Cell Cracked
548-1	1.1	30	Cell Cracked

*Electrical test after welding was not performed

**Weld strength is influenced by silver thickness on joining surface of interconnect--which has some variability due to ion milling process tooling

2.2.6 Selection of Laser Weld Parameters

In the previous section, preliminary welding parameters were established and used in evaluation of the coupling treatments for the three interconnect materials. As a result of this work it was decided to concentrate the effort on the ion-milled molybdenum interconnect and overcome the "dewetting" problem by closer control of the welding parameters.

A quantity of silver-plated molybdenum interconnect material approximately 0.0014 x 0.048 x 1.0 inch was obtained and given an ion-milling treatment to remove the silver from one side of each interconnect in an area of 0.048 x 0.2 in. A laser beam spot size of 1 mm (0.040 in.) was selected to ensure that the laser beam would not "spill-over" the edges of the interconnect and impinge directly on the cell. Since a sharp focus would produce a much smaller spot size (of the order of 0.012 inch) with the 6.0 inch lens the spot was defocussed by moving the lens away from the workpiece until a 0.040 inch spot was produced.

A single pulse of 7.2 milliseconds was selected as the previous studies had shown it to reduce the tendency for "dewetting." The problem of holding the small interconnect in position and in intimate contact with the solar cell was approached by fabricating a small 1-1/2 inch square vacuum plate to hold the solar cell and then placing a 1 mil thick FEP "Teflon" film over both the interconnect and solar cell. The vacuum pulled the film down flat and it held the interconnect in place while the weld was being made. At the point where the laser beam impinged on the FEP film a small bubble usually formed in the film as a result of the heating of the upper surface of the molybdenum. However, this bubble did not appear to interfere with the welding since it occurred after the laser energy had already entered the interconnect.

A series of six welds were then made joining ion-beam milled molybdenum interconnects to the p-side of Solarex 2 mil solar cells to establish the effect of energy inputs ranging from 0.55 to 2.5 J. At 0.75 J a small molten spot was noted on the underside of the interconnect but no welding took place. At 1.0 J a slight "stick" weld was produced which was easily broken to reveal "dewetting" on the underside of the interconnect and a small molten area on the solar cell. Welds made at

1.5 J and over pulled "nuggets," i.e., their strength exceeded that of the solar cell and when stressed tended to fail by tearing out a piece of the cell. A similar series was run with Spectrolab 2 mil solar cells at energy levels of 1.5 to 4.0 J. Welds made at 3.0 J or over damaged the solar cell.

Several welds were then successfully made to the N-contact of Spectrolab 2 mil solar cells at energy levels of 1.0 to 2.5 J. Because of the small area of the N-contact it was necessary to place the laser spot close to the end of the interconnect and in some instances there was a tendency for some of the beam energy to "spill" over the end of the interconnect and impinge on the cell. It was then decided to reduce the spot size on the N-side to about 0.030 inch. This was accomplished by reducing the amount of defocus by focussing at a point 0.3 inch above the interconnect. Because of the higher power density of the smaller spot, the energy level also had to be reduced. It was found that good welds could be made in the range of 0.3 to 0.5 J.

Representative laser welds were examined using both standard optical and scanning electron microscopes. The SEM was found to be particularly useful because of its great depth of field.

Figure 12 shows a weld with a view of the laser input zone. Figure 13 is the bottom view of the cell fragment and interconnect which clearly shows dewetting of silver from the interconnect tab. The resulting bond at the center and edges of the dewetted crater are shown in Figure 14. Figure 15 shows evidence that the interconnect is not touching the cell in the middle, and therefore the weld energy is not transferring into the cell contact. This led to the conclusion that the weld energy was dissipating in the interconnect only, causing it to overheat and dewet.

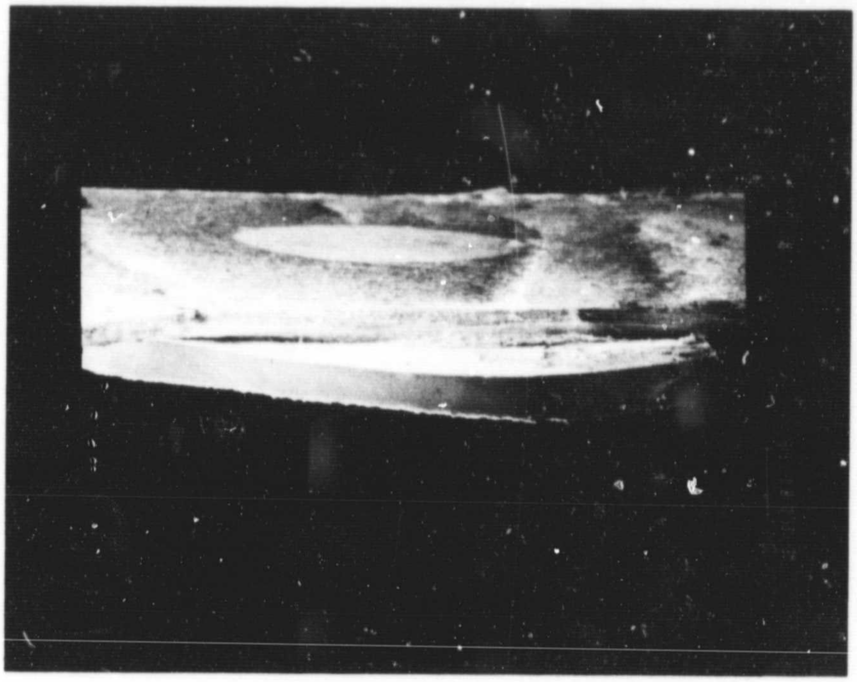


Figure 12 Oblique View Showing Laser Input Zone

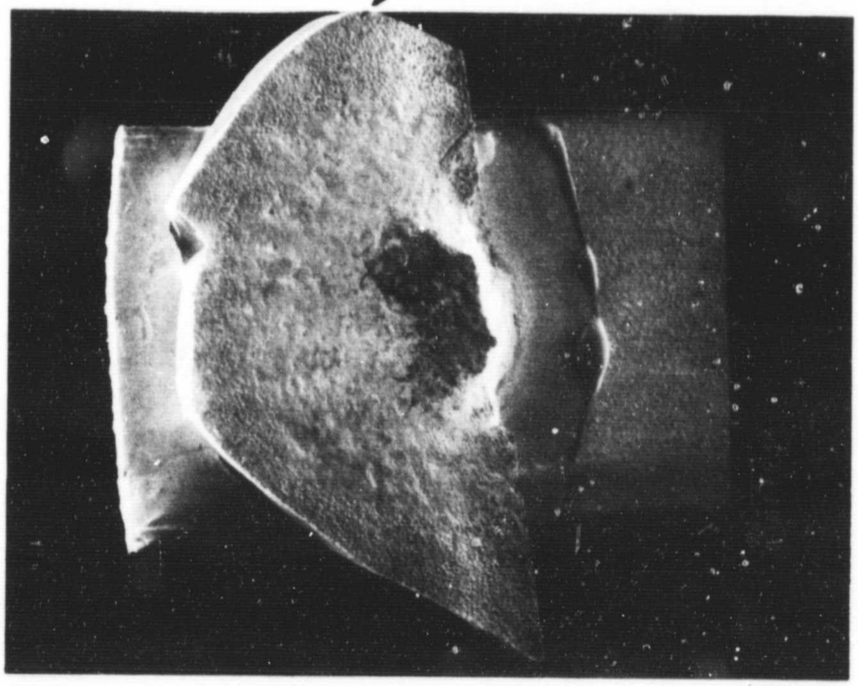


Figure 13 Opposite Side from Laser Showing Silver Dewetting

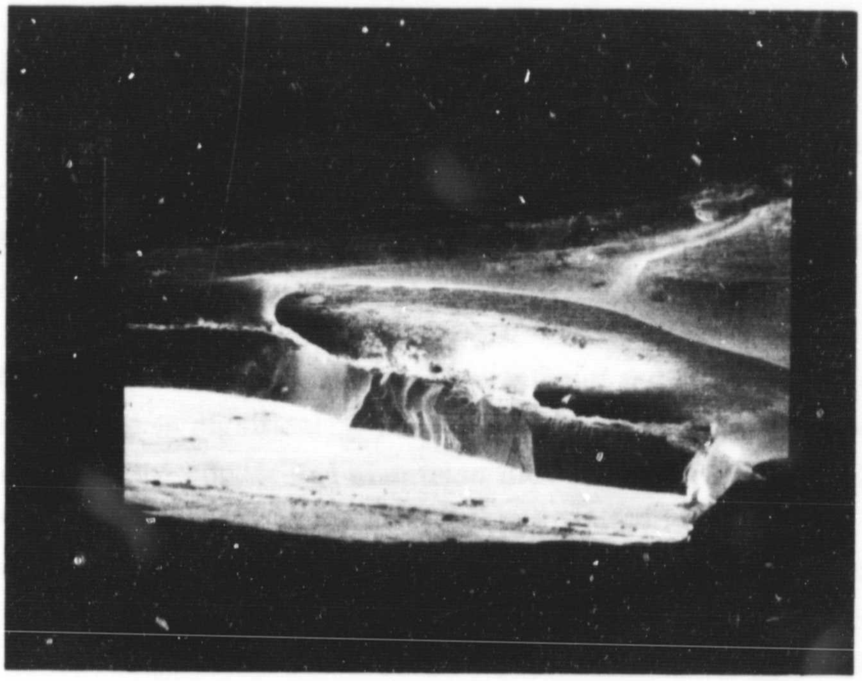


Figure 14 View Showing Dewetted Crater With Bonding at Center and Edges

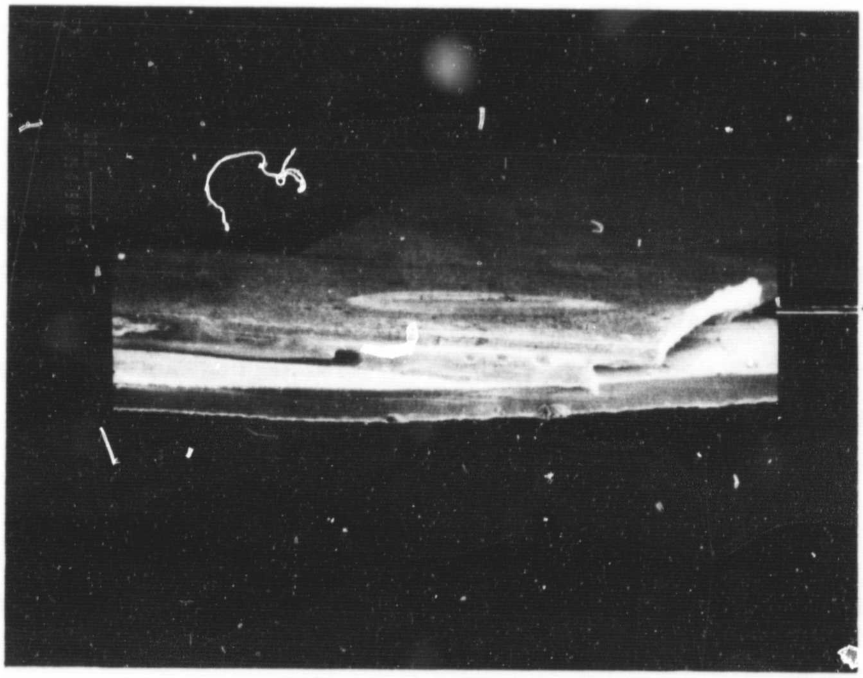


Figure 15 Apparent Bowing Caused By Plated Ridges On Interconnect Edges

2.2.7 Evaluation of Laser Welding

For development of laser welding the effects of laser processing on joint strength and cell performance must be determined. Experiments should be performed on statistically significant quantities of cells to define: 1) P-weld parameters, 2) N-weld parameters, and 3) cell damage thresholds.

Surface treatment of the interconnect to increase absorption of the laser beam energy has been shown to be effective in significantly reducing the power required for welding. However, in the case of both the copper and aluminum interconnects it was found that the Gaussian distribution of the energy in the laser beam resulted in a much higher temperature in the center of the spot which tended to drill a hole through the interconnect, particularly with the shorter 1 millisecond pulse length. The much higher melting point of the molybdenum eliminated the problem of drilling, but the non-uniformity of the temperature across the spot undoubtedly aggravated the tendency for dewetting of the silver on the underside. A beam homogenizer must be incorporated in the system to produce a uniform energy distribution across the spot and reduce the tendency for drilling and dewetting.

In this investigation it was found that ion-milling of the silver plated molybdenum interconnect was an effective means of removing the silver plating in the area of beam impingement so that the beam energy could couple into the molybdenum. However, this operation took up to 1-hour to completely remove the silver and underlying gold flash, and, as noted in the parallel gap section, some silver was also removed from the opposite side. It is recommended that rather than ion-milling, the interconnects be masked off prior to plating, at locations where the beam is to impinge. Absorption of the laser beam energy into the bare molybdenum should be adequate.

To date, almost all investigations of laser welding have utilized either the far infrared $C0_2$ laser at 10.6 microns, the near infrared Nd:YAG at 1.06 microns or the Ruby at 0.694 microns (red). The main reason for this choice is that these lasers are the most practical for producing the high power necessary for welding. However, it has been shown in this investigation that energy levels of 1 Joule or

less are sufficient to produce good high-strength joints in 2-mil solar cells. It is recommended, therefore, that consideration be given to the use of shorter wavelengths where reflection of the laser energy by the interconnect material would be less of a problem. Another advantage to the shorter wavelengths is that they are absorbed to a much shallower depth in silicon, thereby minimizing possible damage to the solar cell from stray radiation during welding of the interconnect.

By use of a frequency doubler it is possible to convert the infrared 1.06 micron Nd:YAG laser beam to a lower powered green 0.532 micron beam which is much more readily absorbed by metals such as gold, copper and silver. Use of such a beam could eliminate the requirement for surface treatments.

2.3 COVER BONDING DEVELOPMENT

During the earlier module technology program LMSC successfully bonded all 64 covers to the coupon simultaneously in vacuum using the CIRT. With the interconnected cells and substrate in place on the CIRT, adhesive was dispensed onto each cell with a syringe. The covers were then placed onto the adhesive with a vacuum pen. Although two of the covers cracked during handling, they were removed and replaced prior to closing the CIRT for evacuation.

The amount of cover bonding adhesive was less than half of that normally used; however, there was still excessive bleed-out. Some of the adhesive flowed around the cell and bonded to the substrate as planned. Some adhesive flowed into the CIRT, impairing the spring action of the spacers. Some adhesive flowed into the asperities of the frosted covers where cleaning is extremely difficult. In orbit any adhesive residue would be darkened by ultraviolet radiation, severely reducing array performance.

It is impractical to clean adhesive residue from covers because of the fragility of the components; therefore, the approach to cover bonding is to control flow of excess adhesive and prevent its migration over the covers.

LMSC investigated several methods for bonding thin covers to interconnected cells using the CIRT. Adhesive control methods considered were:

- Methods of controlling quantity
- Provisions in CIRT for controlling flow
- Disposable bleeder layers to absorb excess
- Scrim layers between cell and cover
- Superstrate continuous covers

2.3.1 CIRT Bonding Test

The CIRT fixture was used to bond 2 mil thick coverslides to 2 mil thick cells with a controlled bond line thickness. Excess adhesive bonded the cells to the polyester laminated Kapton substrate. The bonding procedure for all samples was as follows. The CIRT plate is sprayed with mold release to ease cleaning. A thin (3 to 5 mil) fiberglass cloth is laid down and the pre-punched Kapton/polyester substrate is positioned over this. The cells are loaded into place. The shims in the CIRT plate register the cells. DC 93-500 adhesive is put on top of the cells with a syringe. The coverslides are placed on top of this, also being registered by the CIRT shims. Another piece of fiberglass cloth is placed over this to wick up the excess adhesive. A piece of 1 mil FEP Teflon is placed on top and the cover assembly is put into position. A vacuum is drawn in the fixture while jack screws in the cover keep the cover from completely squeezing down the coverslides until all of the air escapes from between the cells. After a minute the jack screws are loosened and the cover squeezes the coverslides down to the bond line thickness. This is held for approximately 1 minute. The vacuum is removed and the assembly is transferred onto a FEP lined flat plate. Another weighted plate is placed over this and they are cured at 300°F for 30 minutes.

Four 9-cell (3 x 3) and two 6-cell (2 x 3) coupons with a single superstrate were bonded. For each of the samples there was a variation from the above procedure.

The most successful variation for bonding discrete covers used 3 mil fiberglass cloth placed over the cells. Slits had been previously cut into the cloth to allow the shims to pass through it. The coverslides were loaded into the CIRT with a vacuum tool. The adhesive was placed on the coverslide and this was positioned over the cloth and cell. By bringing one edge of the coverslide in against the shims and then releasing the tool vacuum, the coverslides could be placed accurately most of the time. Less handling was required than with the tweezers. When the fixture vacuum was drawn, the excess adhesive squeezed into the cloth. This controlled the adhesive; only a small amount of adhesive flowed onto the top of the coverslides.

For the two superstrate samples the 3 mil cloth was used under the substrates. Very small amounts of adhesive were used. The 2 mil superstrate was positioned over the 6 cells with the vacuum tool and then released. Once the superstrate is positioned, cell misalignment cannot be corrected. It is important to not move the cells when positioning the superstrate.

2.3.2 CIRT Cleaning

To clean adhesive from the lower slots and shims, disassembly of the springs and lock washers is required. The upper shims are removed and wiped clean with trichloroethane. The CIRT and upper slots are cleaned with a short bristle brush (acid brush) and trichloroethane. The shims are replaced and the CIRT is allowed to air dry.

The CIRT has been functionally demonstrated for bonding covers. The amount of adhesive must be carefully metered for complete cell coverage and easy cleaning of the CIRT. The thin fiberglass cloth is also important in controlling the excess adhesive.

2.4 TEST AND DESIGN EVALUATION

2.4.1 Module Test with CIRT

Figure 16 shows the Phase I module under steady state illumination. The added safety that CIRT provides to protect the modules during handling and test has been demonstrated.

2.4.2 Module Design Evaluation

The CIRT offers flexibility to accommodate many different cell sizes and shapes and contact configurations (see Figures 17 and 18). It has been used to produce modules with substrates as well as superstrates. This flexibility permits more freedom in module component selection.

The procedure established during Phase I where equal weight is given to performance parameters, component interactions, and manufacturing processing should be continued. Table 7 shows several module component features which should be developed and evaluated for lightweight modules.

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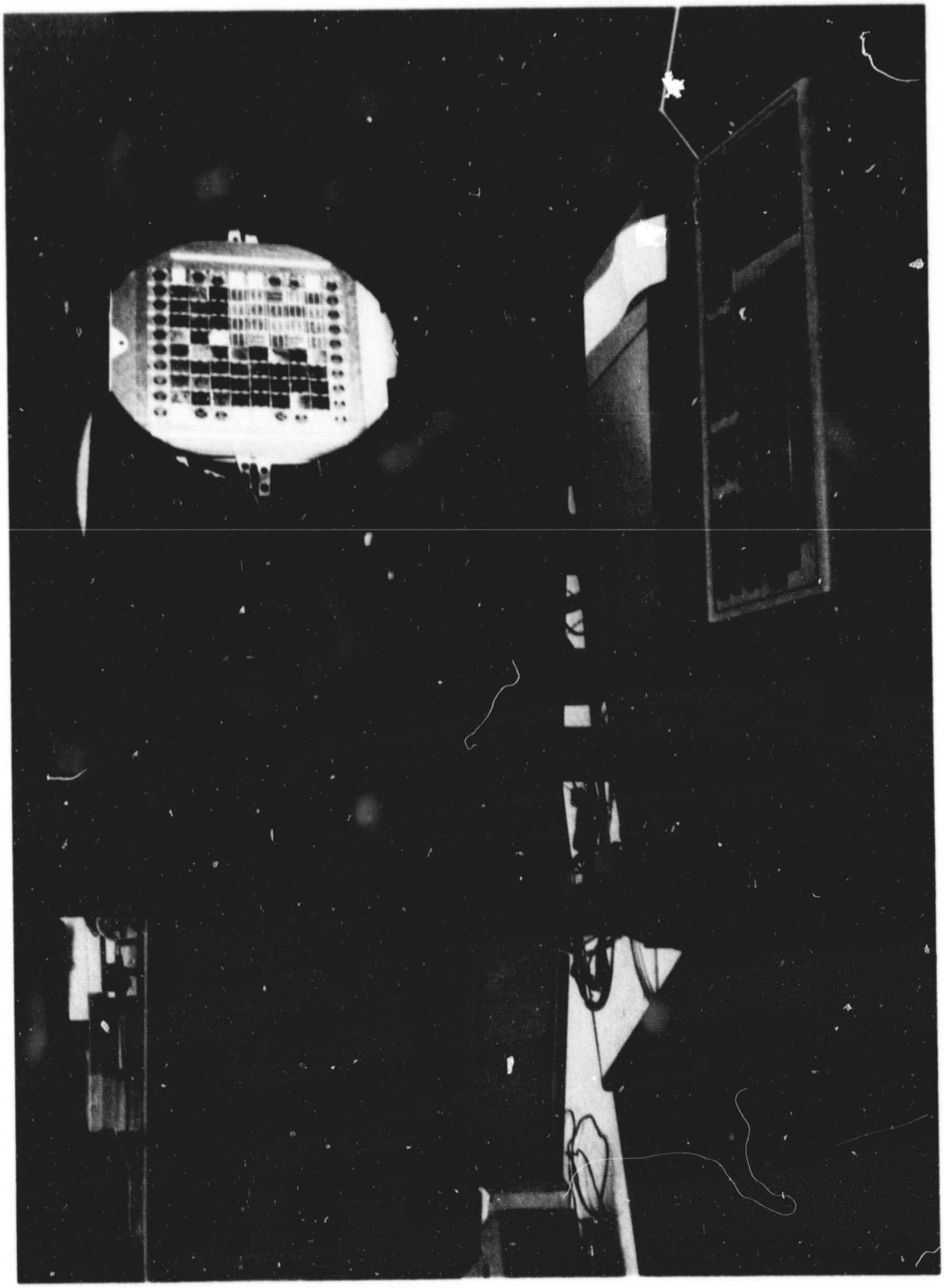

Figure 16 Electrical Test of 2 Mil Module on CIRT in Vertical Position

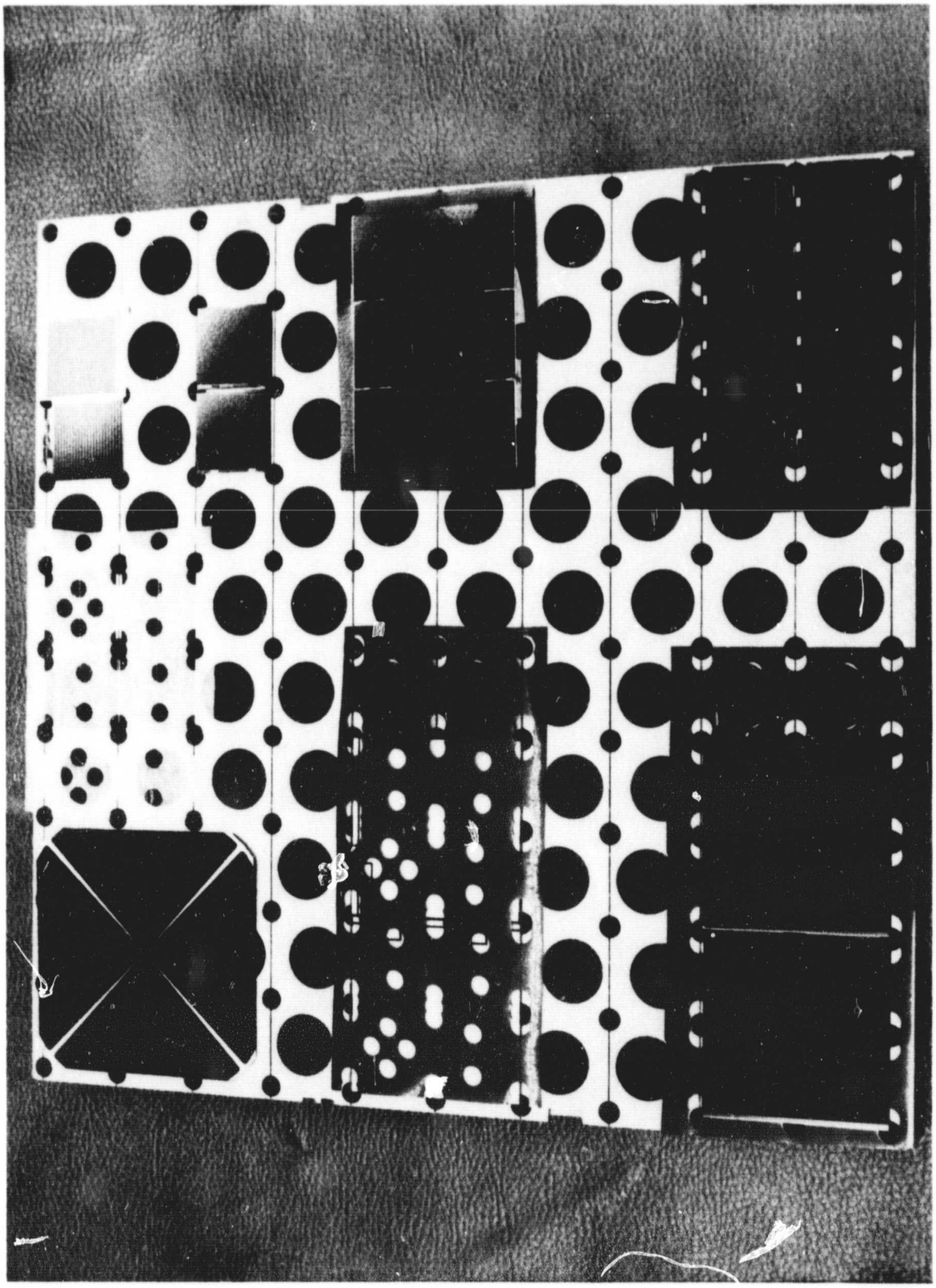

Figure 17 Old CIRT with Several Cell Sizes

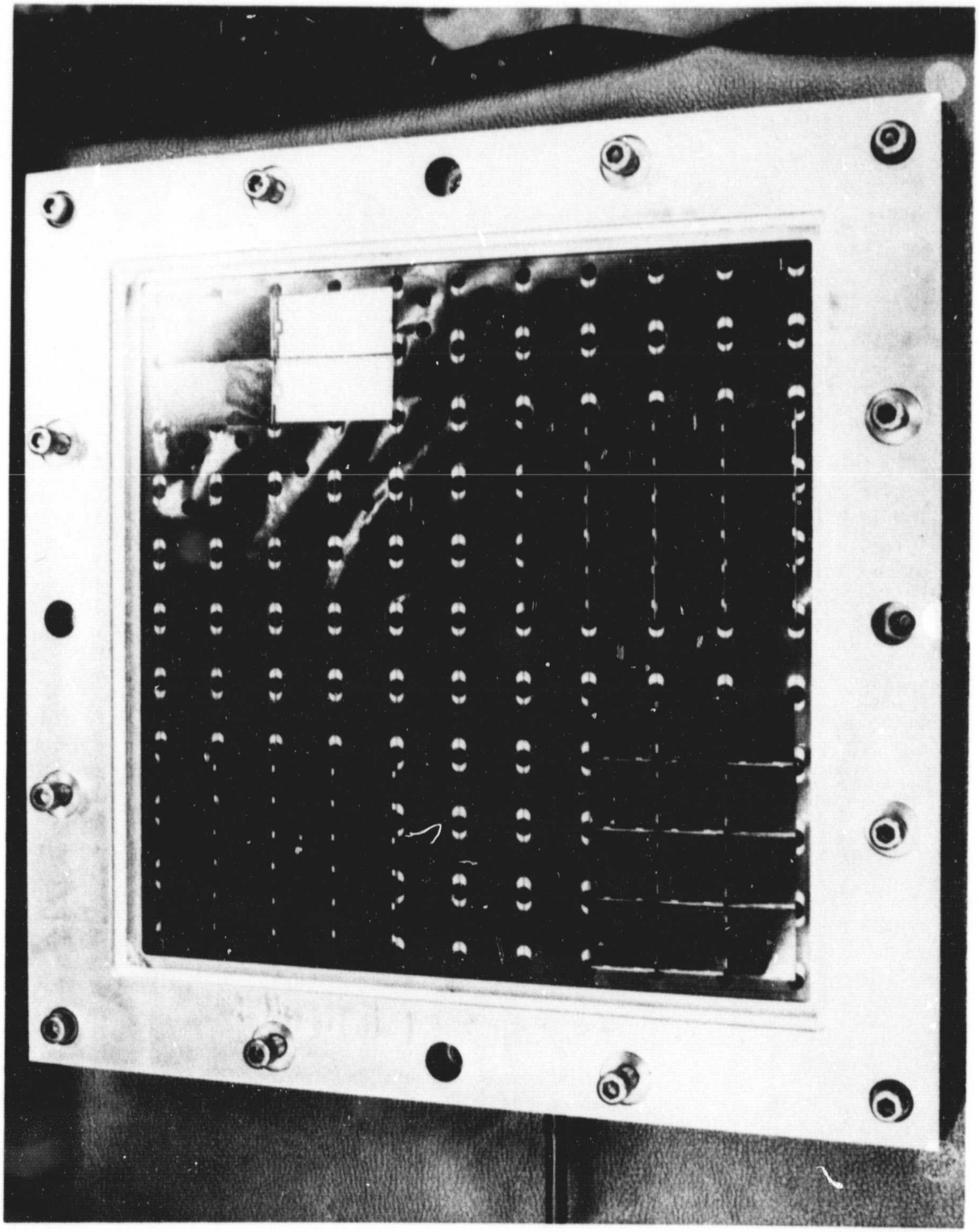

Figure 18 CIRT in New Modified Vacuum Chamber with 2 x 2 and 2 x 4 Cells

TABLE 7

MODULE DESIGN AND STUDY SUGGESTIONS

- CELL
  - Grid P Contact with High ϵ Material Between the Grids
  - Contact Pads Inboard on Cell to Reduce Edge Damage; Arranged to Permit Joint Sensing During Weld
  - Contact Grid and Pads Arranged to Permit Cell Output When Cracked (Redundant Pads Joined by Interconnect)
  - Material Under Contact Pads (with Thermal Expansion Coeff $\geq$ Si) to Insulate and Protect Cell/Junction
- SUBSTRATE
  - Ribbon to Reduce Weight
  - Insulator for Interconnect
  - Registration for CIRT, Interconnect, Cells
- INTERCONNECT
  - Redundant Attachment to Cell Contact Pads
- COVER
  - Superstrate to Reduce Cost and Improve Radiation Protection
- STUDY SUGGESTIONS
  - Bonding Interfaces, Joint Properties, and Expansion Coefficients
  - Co-planar Contact Cell Variations to Permit Single Side Processing
  - Cover Installation Methods and Crack Propagation Properties

3.0 CONCLUSIONS

The feasibility of utilizing 2 mil cells in ultralight modules has been demonstrated by fabricating several modules with different components, and processing methods. During this phase LMSC has further developed the CIRT, laser welding, and cover bonding.

The Cell Interconnect Registration Tool (CIRT) is proven to be a module fabrication aid which permits broad flexibility in module design. The flexibility includes areas of panel and circuit design as well as component and process selection.

Feasibility of laser welding of interconnects has been demonstrated. The technology requires further development in the areas of equipment and process parameters. Laser weld joints of good strength have been produced. The problem of coupling laser energy into the components is now well defined, and the equipment required for further development is defined. More work is required to understand contact/interconnect interface surface requirements for good adhesion.

Procedures for bonding coverslides in vacuum using CIRT have been developed for discrete covers, superstrate covers, and "scrim" layers between cell and covers. The quantities of adhesive have been greatly reduced; and the control of excess adhesive has been demonstrated.

4.0 RECOMMENDATIONS

Phase I demonstrated the feasibility of using 2 mil cells in modules which could, with appropriate modifications, produce up to 600 watts/kg, and developed the CIRT which made manufacturing the modules practicable. Phase II improved the CIRT, proved feasibility of both laser welding and vacuum bonding of covers.

These successes lead LMSC to recommend a panel segment demonstration program which would produce and test panel segments. The goal of the program would be to design, manufacture, and test a panel which demonstrates the ultimate, practical power to weight performance for array blankets. During design definition the suggestions in Table 7 provide a starting point.

5.0 NEW TECHNOLOGY

No new technology was developed during this contract phase.